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Development and application of the integrated SWAT–MODFLOW model

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Summary This paper suggests a new approach for integrating the quasi-distributed watershed model, SWAT, with the fully-distributed ground-water model, MODFLOW. Since the SWAT model has semi-distributed features, its groundwater component does not consider distributed parameters such as hydraulic conductivity and storage coefficient. In generating a detailed representation of groundwater recharge, it is equally difficult to calculate the head distribution and the distributed pumping rate. In order to solve this problem a method is proposed whereby the characteristics of the hydrologic response units (HRUs) in the SWAT model are exchanged with cells in the MODFLOW model. By using this HRU–cell conversion interface, the distributed groundwater recharge rate and the groundwater evapotranspiration can be effectively simulated. By considering the interaction between the stream network and the aquifer to reflect boundary flow, the linkage is completed. For this purpose, the RIVER package in the MODFLOW model is used for river–aquifer interaction. This combined modeling is applied to the Musimcheon Basin in Korea. The application demonstrates that an integrated SWAT–MODFLOW is capable of simulating a spatio-temporal distribution of groundwater recharge rates, aquifer evapotranspiration and groundwater levels. It also enables an interaction between the saturated aquifer and channel reaches. This interaction played an important role in the generation of groundwater discharge in the basin, especially during the low flow period. The advanced water transfer method in SWAT–MODFLOW was successfully tested, and reproduced the

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distributed drawdown and reduced stream flow by pumping with multiple wells. Therefore, when considering discharge to streams, springs or marshes, the use of this model would be beneficial in planning for the sustainable development of groundwater.

Introduction

In Korea, there has recently been considerable debate surrounding current issues related to the use of groundwater. These issues focus on various factors such as the use of groundwater near streams, water rights (and regulations) on the use of groundwater near streams, the groundwater recharge rates, what should be considered as reasonable groundwater development, instream flow and groundwater dam construction. Without a suitable understanding of the hydrologic components for the planning of water resources, many problems may arise when attempting to establish lower level planning and water resource security. These problems might eventually lead to complications and inaccurate predictions. Until now, hydrologic component analysis in Korea has concentrated on the management of surface water, while problems related to groundwater have not been managed in a rigorous manner. Furthermore, the groundwater model used in previous analyses was not adequately linked to surface water analysis. The main focus in these previous studies has been primarily on aquifer management. For example, groundwater recharge could not be considered in terms of hydrological processes, which are directly related to precipitation, evapotranspiration and surface runoff. Groundwater recharge rate was an input to the groundwater model and has therefore been determined from trial and error during calibration.

The best solution for solving this problem is the construction of a long-term rainfall runoff model that can effectively produce an integrated analysis for both the groundwater and the surface water. The main factors to consider for these kinds of models are the land use, surface runoff, and other factors such as climate change. It is essential for the model to be able to examine the hydrologic effects while concurrently allowing hydraulic interaction between surface water and groundwater. In addition, when analyzing groundwater behavior, it is important to simulate the spatial occurrence and distribution of return flow. The fully combined SWAT–MODFLOW model is specifically developed for this purpose (Kim et al., 2004a, b).

In this study, the SWAT (Arnold et al., 1993, 1998; Arnold and Fohrer, 2005) model and the MODFLOW (McDonald and Harbaugh, 1988) model were integrated in order to calculate the quantity of groundwater discharge determined by hydrologic analysis from the watershed. The SWAT model is widely used for long-term runoff and water quality simulations. It was originally developed from the CREAMS (Knisel, 1980) and SWRRB (Williams et al., 1985) models with channel routing and groundwater components added for larger watersheds.

Gassman et al. (2007) reported an extensive review of the history of the SWAT model. According to the review, SWAT has undergone a continued review and expansion of capabilities since it was created in the early 1990s. Arnold and Fohrer (2005) and Neitsch et al. (2005a) described key enhancements for previous versions of the model (SWAT94.2, 96.2, 98.1, 99.2, and 2000). Documentation for some previous versions of the model is available at the SWAT web site (SWAT, 2007). Neitsch et al. (2005a, 2005b) provide a detailed theoretical documentation and a user manual for the latest version of the model (SWAT2005). In this study, AVSWAT2000 (DiLuzio et al., 2001) is used, with some modifications.

While SWAT has its own module for groundwater components (Arnold et al., 1993), the model itself is lumped and therefore distributed parameters such as hydraulic conductivity distribution could not be represented. Moreover, the SWAT model creates difficulties when expressing the spatial distribution of groundwater levels and recharge rates.

One of the most essential components of an efficient groundwater model is the accuracy of recharge rates within the input data. The conventional groundwater flow analysis performed by MODFLOW often overlooks the accuracy of the recharge rates that are required to be calculated into the model. Consequently, there is considerable uncertainty in the simulated groundwater flow results.

For the Rattlesnake Creek basin in south-central Kansas, Sophocleous et al. (1997, 1999) have previously presented an interface between SWAT and the MODFLOW called SWATMOD, which is capable of simulating the flow of surface-water, groundwater, and stream–aquifer interactions on a continuous basis. Perkins and Sophocleous (1999) describe drought impact analyses using this system. This system was modified to become a two-way coupling system and was used by Sophocleous and Perkins (2000) to investigate irrigation effects on streamflow and groundwater levels in the lower Republican River watershed in north central Kansas. It was also used on streamflow and groundwater declines within the Rattlesnake Creek watershed. Conan et al. (2003) applied coupled modeling of SWAT with MODFLOW to the Coet-Dan watershed in Brittany, France. Menking et al. (2003) studied the combined SWAT runoff results with previous estimates of groundwater flow (Shafike and Flanigan, 1999), and employed the MODFLOW-LAK2 package (Council, 1999) to assess the modern hydrological balance of the Estancia Basin. Menking et al. (2004) performed additional analyses of Lake Estancia for the Last Glacial Maximum period. Galbiati et al. (2006) presented the application of the watershed scale model SWAT, linked with MODFLOW, to the Bonello coastal basin in Northern Italy. The model application was successful in predicting the presence of water and nutrients leaching from the surface to the aquifer, as well as the groundwater dynamics, the aquifer interactions with the stream system, and the surface water and nutrient fluxes at the watershed outlet.

In this study, the newly integrated SWAT–MODFLOW model is described and demonstrated. We developed an HRU–cell conversion interface, which exchanges flow data between the cells in MODFLOW and the HRUs (hydrologic response units) of SWAT. HRUs are defined by overlaying soil and land use and lumping together similar soil/land use combinations. On the basis of these modifications, the groundwater model in SWAT was replaced with MODFLOW. Therefore, it was possible to establish a fully combined modeling program, which is able to form a linkage in each time step. SWAT—MODFLOW uses MODFLOW for groundwater analysis instead of the groundwater module of SWAT. Therefore, SWAT—MODFLOW is used to simulate the spatio-temporal distribution of groundwater recharge rates and groundwater evapotranspiration. SWAT—MODFLOW is also capable of analyzing interactions that take place between the stream network and the aquifer. The groundwater components of MODFLOW can be expressed as the three-dimensional groundwater flow equation. Other factors can be taken into account, such as the complex geological structure, the boundary condition and various hydraulic characteristics. Consequently, the spatial distribution of the groundwater head can also be represented. The amounts of exchange rate between the stream—aquifer, computed by the MODFLOW model (the net groundwater discharge), and the amount of surface runoff, calculated by the SWAT model, are computed in order to determine the estimate total discharge of the watershed. This integrated model was successfully applied to the Musimcheon Basin in Korea, reproducing new application results. It also compares the integrity of the results generated from both the SWAT and SWAT—MODFLOW models.

Development of the integrated SWAT—MODFLOW model

Overview of SWAT and MODFLOW models

SWAT is a basin scale, continuous time model that operates on a daily time step. It is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds. The model is physically based, computationally efficient, and capable of continuous simulation over long time periods. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple sub-watersheds. These are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the sub-watershed area and are not identified spatially within a SWAT simulation (Gassman et al., 2007).

MODFLOW (McDonald and Harbaugh, 1988) is a well-known and widely used modular three-dimensional block-centered finite difference code used in layered aquifer systems. MODFLOW is physically based since it combines Darcy's law and the mass balance for subsurface flow. MODFLOW is able to represent a number of aquifer conditions, including confined, unconfined, leaky, delayed yield, and variably confined/unconfined conditions. Both steady state and transient conditions can be simulated. The option for deactivating regions within the domain permits the modeler to design complex irregular systems with ease. The model can account for all the common boundary conditions generally encountered in practice. These include fixed or pressured heads, variable or constant fluxes, groundwater recharge/discharge, point withdrawals, and drains. Several surface—subsurface interactive processes such as evapotranspiration and river—aquifer interactions can also be adequately simulated by MODFLOW (Sophocleous et al., 1997).

The SWAT model is particularly limited in terms of dealing with groundwater flow, due to its lumped nature. Conversely, MODFLOW has difficulty in computing the distributed groundwater recharge, which is a major input for groundwater modeling. Therefore, by sustaining the advantages of the two models, it is possible for the hydrological components to be reasonably quantified. If an HRU-based groundwater recharge is used for input data in MODFLOW, and the groundwater flow between the aquifer and the stream is computed and exchanged to SWAT, then the spatio-temporal characteristics in the watershed will be properly reflected. A schematic diagram of this is shown in Fig. 1.

Structure of the integrated SWAT—MODFLOW model

SWAT and MODFLOW are divided into two components. These are the input component and the computation component. The purpose of this division is to include MODFLOW into the groundwater module of SWAT. This process is shown in Fig. 2. For this purpose, SWAT is divided into two modules, before and after the subroutine 'simulate' which contains the loops governing the modeling of processes in the watershed and MODFLOW is embedded as a subroutine. Subroutine 'gwmod' is associated with groundwater flow, which is computed based on recharge from each HRU in SWAT. As MODFLOW does not have any division of sub-basins or HRU, an alternative method is required in order to use the HRU-based groundwater recharge in SWAT as the input for MODFLOW. Therefore, SWAT is split before and after the 'gwmod' subroutine. As 'gwmod' subroutine is called by HRU for each time step (one day), gwmod is not easily disassembled into two parts, such as input and computation. We reconstructed the original 'gwmod', so that the variables calculated before calling the gwmod subroutine could be used after calling the gwmod subroutine. This modification makes the exchange of variables possible.

The main program of the SWAT—MODFLOW model is simply a modified version of the main program of SWAT. The SWAT—MODFLOW model begins by initiating SWAT and it then reads the input data which are required to initiate SWAT. The main computation of SWAT is applied to the 'simulate' sub-program, and different subroutines are implemented. When MODFLOW is implemented, the groundwater recharge of the cell from HRU and the river stage of the cell are used for input in MODFLOW. After implementing MODFLOW, the outputs of the cells (cell-based recharge, aquifer evapotranspiration, and exchange rate between river and aquifer) are added via the HRU and channel, and sent to SWAT. In the integrated model, the recharge rate of the cell and river stage is used as input data for MODFLOW from SWAT.

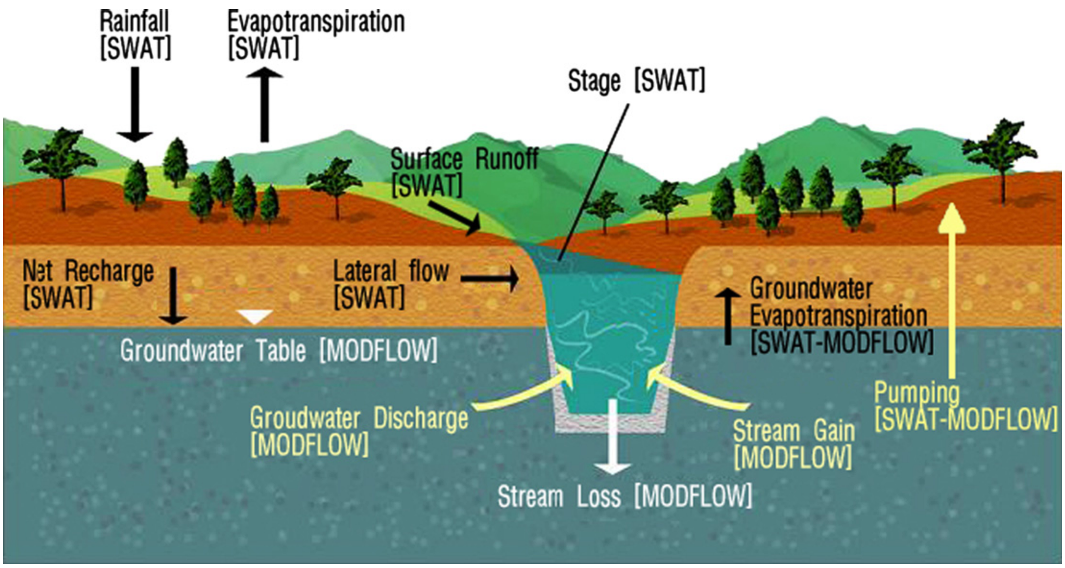

Figure 1 Schematic diagram of combined surface water and groundwater model.

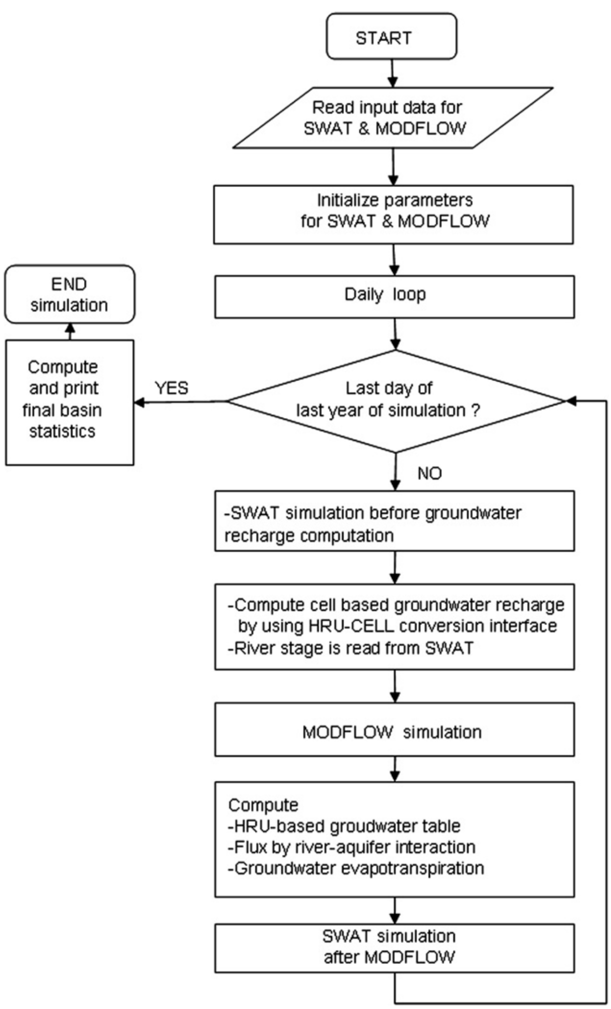

Figure 2 Flowchart of computation of combined SWAT and MODFLOW models.

HRU—cell conversion interface using GIS

Since heterogeneities, which occur in soil, vegetation, land use and other factors, exist within sub-basins, a practical alternative is needed that will statistically represent the effects of these heterogeneities. SWAT uses the hydrologic response unit (HRU) concept (Leavesley et al., 1983). These HRUs are statistically defined soil-vegetation/land use spatial complexes with a distinct hydrologic response. Therefore, each sub-basin is discretized into virtual areas (Mamillapalli et al., 1996), without reference to their spatial positioning within the sub-basin, with each area having a unique soil and land use combination (Sophocleous and Perkins, 2000).

The AVSWAT2000 modeling was supported by data organized in ArcView (ESRI, 1997, 1999) Geographical Information System (GIS) databases. GIS data provides basin conditions such as basin topography, land use, soils, stream conditions, etc. With AVSWAT2000, the HRUs within the sub-basins are determined by overlaying the land use map and soil map in pre-processing. During this process, HRU numbers are calculated by combining spatial soil and land use attributes, which are indicated by numbers in each sub-basin. Since soil and land use numbers have their own spatial addresses, the HRU numbers could be inversely assigned. By using this concept, the HRU—cell conversion interface is developed. Fig. 3 shows the procedure for creating the spatial position of the HRU numbers that are used for the MODFLOW input. With the AVSWAT 2000 pre-processing menu, land use and the soil map can be exported to ASCII files, which have their own spatial position numbers. After overlaying these two maps, AVSWAT2000 makes an HRULanduse-SoilRepSWAT.txt file. This text file contains information on the combination of soil and land use attributes. By using this information, creating the reference to the HRU spatial positioning within sub-basins is possible. As shown in Fig. 3, land use and the soil map are exported to an ASCII file, which has its own spatial numbers with

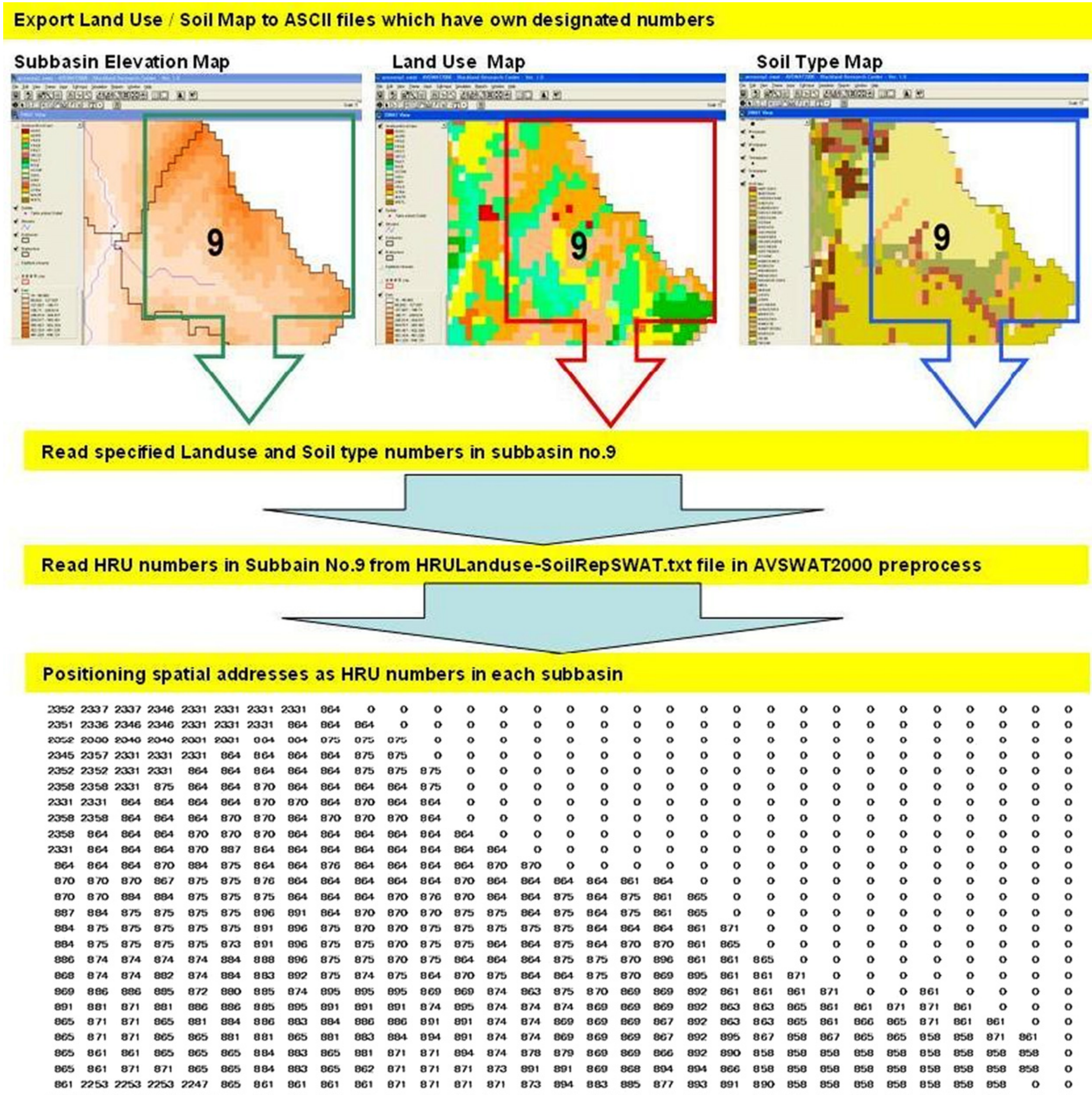

Figure 3 Schematic diagram of HRU—cell conversion interface.

the same sized cells determined by DEM. Subsequently, the conversion interface reads the HRU numbers in sub-basin No. 9 from the HRULanduse-SoilRepSWAT.txt file in AVSWAT2000 pre-process output and assigns these HRU numbers as spatial addresses in the associating cells in MODFLOW. In Fig. 3, the number zero designates the area outside of the boundary of MODFLOW modeling.

Spatial distribution of groundwater recharge rate

When using SWAT, groundwater recharge rates of the HRU within a sub-basin do not contain spatial information. As previously mentioned, the HRU spatial distribution map is made by overlaying the soil map and the land use map in order to distribute the recharge values of the HRU to the cells in MODFLOW by using the RCH package. For this purpose, the HRU number is used as the zoning number in the Basic package of MODFLOW (*.bas file). HRU distribution maps are used to assign the recharge values of HRU from SWAT to each cell as the average area values of the cell. Fig. 4 shows the schematic diagram of groundwater recharge computation in SWAT—MODFLOW.

Groundwater evapotranspiration

Water may move from the shallow aquifer into the soil profile via soil evaporation (capillary uptake) and plant root uptake, where the saturated zone is close to the surface where deep-rooted plants are growing. This rising water is defined as 'Revap' in the SWAT model (Arnold et al., 1993). The amount of revap is modelled as a function of the water demand for evapotranspiration. Revap is only permitted to occur when the amount of water stored in the shallow aquifer exceeds the specified threshold value. However, in SWAT

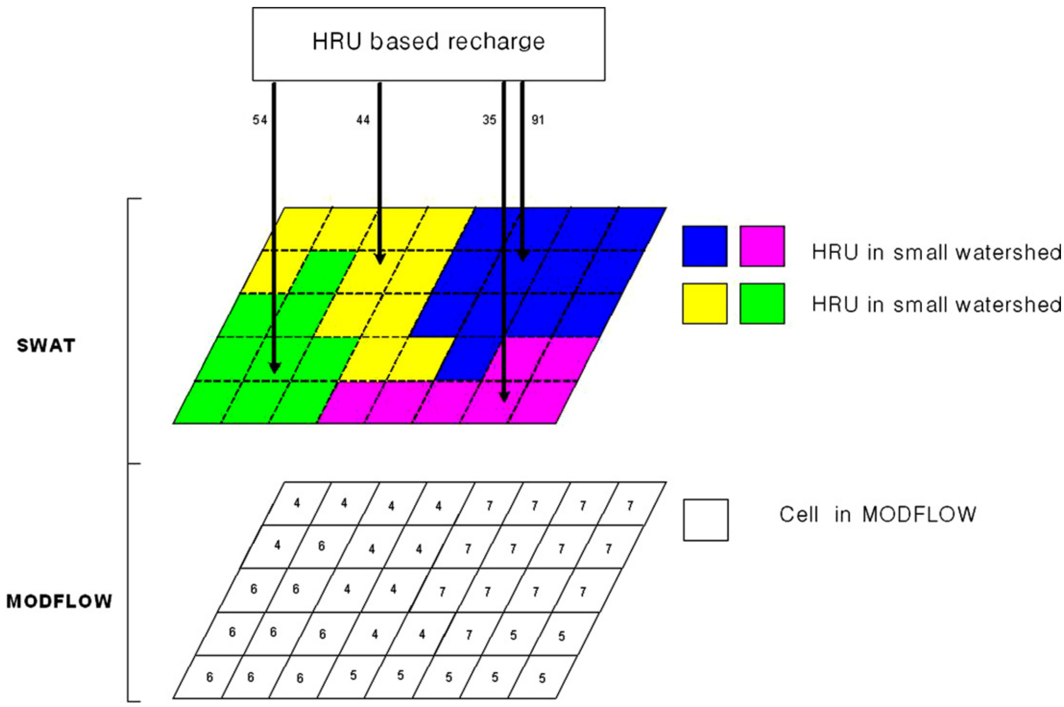

Figure 4 Schematic diagram of recharge computation in SWAT—MODFLOW.

model, revap is lost to the atmosphere to such an extent that it is not directly linked to the water content in the soil profile. In order to represent the direct interaction between the shallow aquifer and the overlying soil zone, the coupling groundwater uptake to the soil water content has been prepared in the SWATMOD model (Sophocleous and Perkins, 2000). The daily uptake from shallow groundwater is distributed over the soil profile, beginning at the bottom layer. The volume of uptake for each time step is calculated by using the EVT package in MODFLOW as a linearly varying function of depth to the water table. It has a maximum rate at the ground surface and a minimum rate at the root zone depth. The maximum uptake rate can be specified by potential evapotranspiration computed by SWAT. This coupling process is effective in SWATMOD when the groundwater table is within the root zone. In this study, SWAT—MODFLOW also follows the above procedure, as suggested by Sophocleous and Perkins (2000), in order to cope with the upward water movement from the shallow aquifer to the soil zone, as demonstrated in Fig. 5.

Some improvements were accomplished in the current work to enhance the coupling of shallow groundwater and soil water content. If the simulated groundwater table rises within the root zone, a critical problem occurs because two control volumes of the soil zone and the shallow groundwater zone are overlapped. In order to treat this overlapped area, we consider the area as a fraction of the soil water zone or the shallow groundwater zone. If the overlapped area is regarded as the soil water zone, the water content within the overlapped area is governed by the soil water routing procedure in SWAT. Therefore, the Sophocleous and Perkins (2000) method is effective for handling the soil and plant uptake from shallow groundwater. If the area is regarded as the shallow groundwater zone a soil zone, then the water within the overlapped area is governed by the groundwater flow equation in MODFLOW. In this case, special treatments are required. Fig. 6 shows a schematic diagram of groundwater evapotranspiration. The fraction of soil zone below the water table is excluded from the initially defined soil zone and replaced by the shallow groundwater aquifer as shown in Fig. 6a. Hence, no percolation or lateral subsurface flow in the overlapped area is allowed. In SWAT—MODFLOW, the interactive procedure for representing the upward movement from the shallow aquifer to above the soil zone is divided into two processes. In the first process, it is permitted for water to be removed from the shallow aquifer to the atmosphere by direct plant-root uptake when the water table is within the root zone. This removed water corresponds to the area of AOE in Fig. 6b.

In the second process, some of the shallow groundwater is taken back into the soil layer via capillary uptake under the assumption that the soil layer above the water table is filled to field capacity.

The volume of water extracted by plant-rooted uptake and capillary uptake is used as one of the boundary conditions of MODFLOW's simulation. When the cell-based groundwater table is computed, the HRU based groundwater table is obtained by averaging the cell-based groundwater levels of each of the HRUs. Thus, a groundwater uptake routine is operated when the HRU-based groundwater table is within the root zone.

River—aquifer flow exchange rate by SWAT—MODFLOW

In SWAT, if the depth of a shallow aquifer increases above the user defined threshold value, it is assumed that groundwater discharge is occurring. Conversely, the groundwater

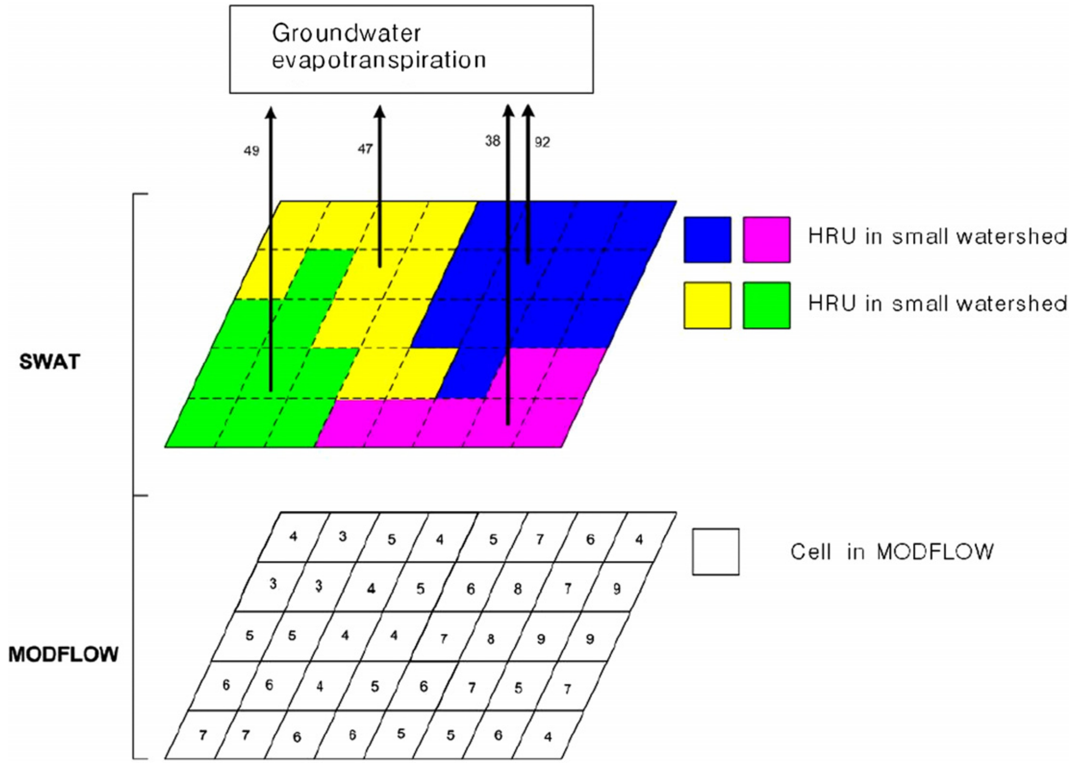

Figure 5 Schematic diagram of groundwater evapotranspiration computation in SWAT—MODFLOW.

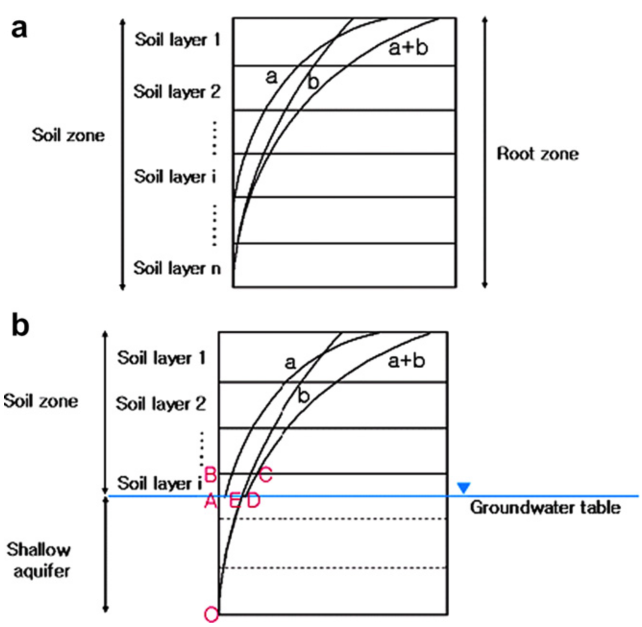

Figure 6 A schematic diagram of groundwater evapotranspiration. (a) Initially defined soil zone and (b) adjusted soil zone by rising groundwater table (a: depth distribution of water uptake by potential evaporation, b: depth distribution of water uptake by potential transpiration, ABCD: evapotranspirative water demand at soil layer i, OAE: transpirative water demand).

flow rate from the river to the aquifer cannot be computed if the depth of the shallow aquifer is lower than the threshold value. This problem is caused by the inability of SWAT to use riverbed elevation and aquifer depth values. However, MODFLOW is able to manage the river—aquifer flow exchange by comparing the river stage and groundwater levels, which are computed by using riverbed elevation and the aquifer depth. River—aquifer interaction can be simulated using the River package in MODFLOW.

The major input data used in the experiment conducted in the MODFLOW River package were the row and column of cells for the river, the river stage, the conductance of the riverbed and the riverbed elevation. Among these variables, river stage and conductance of the riverbed are read directly from SWAT. The user is able to modify these. The sum total of the riverbed elevation and the river stage are computed by SWAT. This total is the river stage value, which is used in the MODFLOW's River package. The conductance of the riverbed is computed by using the hydraulic conductivity, width and length of the channel, which are the input data for SWAT. The user is able to read the thickness of the riverbed. The river length in MODFLOW represents the length of the corresponding main channel in SWAT. To match the channel of SWAT with the river cells of MODFLOW, river network in DEM is used and read by MODFLOW. The exchange rate in each cell is computed by adding the contributed groundwater flow to the river and the contributed river flow to the aquifer for each respective channel of SWAT. The exchange flow rate between river and aquifer is converted and returned to the flow rate in the channel of SWAT. Fig. 7 illustrates a schematic diagram of the river—aquifer interaction in SWAT—MODFLOW.

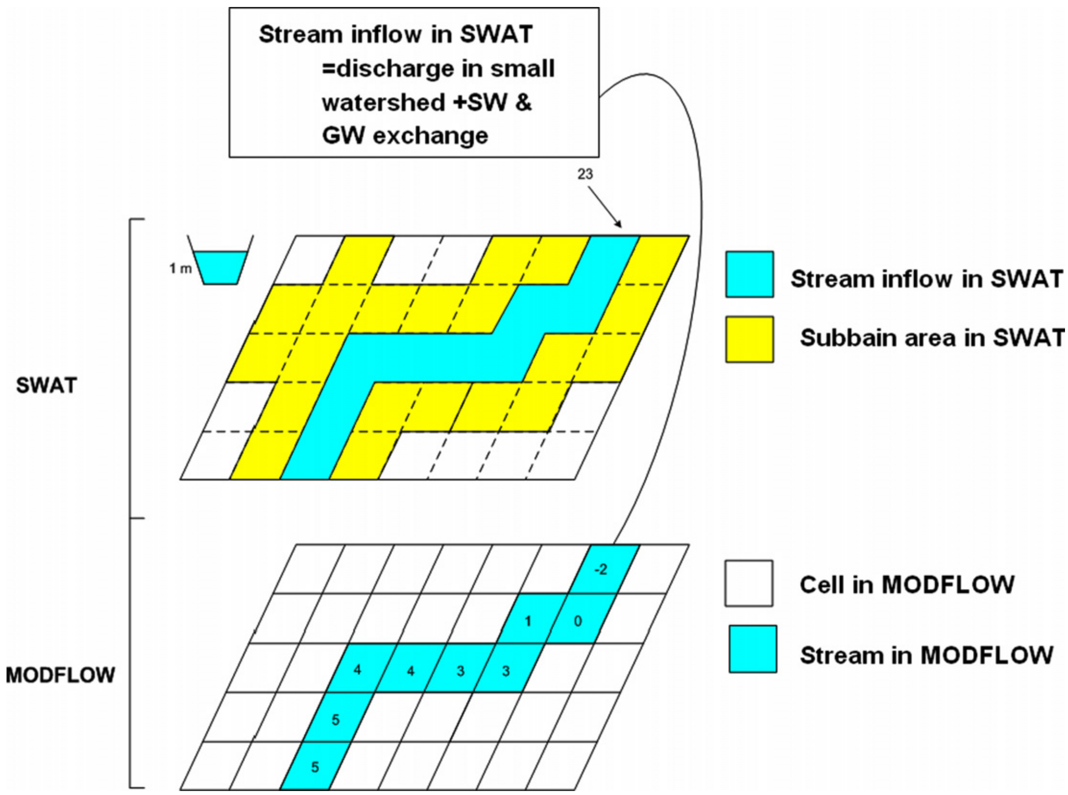

Figure 7 Schematic diagram of river—aquifer interaction.

Water transfer by pumping in SWAT—MODFLOW

In SWAT, water can be transported into, or out of, the watershed by means of irrigation, water transfer, and point source or by inlet discharge or consumptive water use.

In water transfer, different sources of water can come from the shallow aquifer, deep aquifer, reach, reservoir and outside of the watershed. As for the destination of water, the source can be transferred to the HRU, reach, reservoir, and aquifer or to outside of a watershed. In this study, considering the different types of water source and destination enhances water transfer methods.

In SWAT, if the source type is either aquifer, reach or reservoir and the destination type is outside of the watershed, then SWAT can handle this water transfer by using the consumptive water use option. In this case, water can be removed from the watershed at a constant monthly rate. In order to overcome this limitation, this study proposes using the method of removing water from the watershed by means of the ''water transfer'' command in SWAT. This method uses daily/monthly/yearly options as well as either the constant amount, constant rate or minimum value used for water transfer from the water source. If the source type is outside the watershed and the destination type is a reservoir, SWAT can add water to the reach in which the reservoir is located. The associated source code in SWAT (subroutine transfer) was modified in order to consider the direct water transfer from various water sources such as aquifer, reach, and reservoir, without using the command of ''point source and inlet discharge''.

If the source is the shallow aquifer, then the water transfer method is related to the Well package in MODFLOW. The ''water transfer command'' in SWAT, which is linked with the Well package in MODFLOW, is used in order to simulate the water transfer by pumping. The Well Package in MODFLOW can be used to simulate wells which either withdraw water from the aquifer or add water to it at a specified rate during a given stress period. At the beginning of each stress period, the Well Package is executed subsequent to reading input variables for each well. These variables include the row, column and layer number of the cell in which the well is located. The discharge or recharge rate of the well is also read before implementation. If any water is removed from the aquifer by pumping, the discharged water can be transferred to any destination. This is performed with a water transfer command in the watershed configuration file of the SWAT.

The locations of each water source are matched to the well cells in MODFLOW and the locations of the receiving water bodies are set as specified reaches in different subbasins.

Construction of input data for SWAT—MODFLOW

The combined SWAT—MODFLOW model is tested in the Musimcheon Basin, which has an area of 198 km^2. This drainage basin is divided into 34 sub-basins, and the area of each sub-basin ranges from 1.38 to 12.14 km^2, while the channel lengths of each sub-basin ranges from 0.3 to 5.7 km. The SWAT model requires inputs on weather, topography, soils, shallow aquifer, land use and management and stream channels, etc. AVS2000 (DiLuzio et al., 2001) was used to automate the development of model input parameters. The DEM of the Musimcheon Basin is shown in Fig. 8.

Daily precipitation for the Cheongju gauging station, which covers the entire watershed, were obtained from the hydrologic database of MOCT (Ministry of Construction and Transportation). Daily values of maximum and minimum temperatures, solar radiation, wind speed, and relative humidity were collected from the weather service data of the KMA (Korea Meteorological Administration). Land use digital data (1:25,000) were used from the National Geographic Information Institute of MOCT (Fig. 9a). Fifteen land cover classes are found in this watershed. The area and the portion of the land use classes are specified in Table 1. The detailed soil association map (1:25,000) from NIAST (National Institute of Agricultural Science and Technology) was used for the selection of soil attributes (Fig. 9b). Sixty hydrologic soil groups within the Musimcheon Basin were used for analysis (Table 2). Relational soil physical properties such as texture, bulk density, available water capacity, saturated conductivity, soil albedo, etc., were obtained from the Agricultural Soil Information System (<http://asis.rda.go.kr>) of NIAST (2005).

HRUs in SWAT are formed based on the land use (Fig. 9a) and hydrologic soil group (Fig. 9b) and as shown in Fig. 9c.

However, due to the semi-distributed features of SWAT, spatial locations of each HRU within sub-basins are not determined. Hence, so as to reflect the HRU locations to MODFLOW, spatially distributed HRUs are used by means of the above mentioned HRU—cell conversion interface, with a cell-size of 100 m. This matches the discretized watershed with the MODFLOW grids. Within MODFLOW, the aquifers are represented as three layers, discretized into a grid of 223 rows and 214 columns. The first layer represents the unconfined alluvial aquifer, while the second and third layers represent the confined/unconfined rock aquifers.

Groundwater information from the National Groundwater Information Management and Service Center was used to determine the aquifer characteristics for MODFLOW inputs. Hydraulic conductivity of the alluvial layer used in the model ranged from 1.3 to 39 m/day, while that of the rock layers ranged from 0.01 to 2.2 m/day. The estimated specific yield ranged from 0.1 to 0.3 for the alluvial layer and 0.01—0.03 for the rock layers (Freeze and Cherry, 1979). The conductance of the riverbed was determined as one tenth of the alluvial aquifer via a trial and error procedure.

Groundwater limits for the model corresponded to those of the surface water basin. These boundaries were designated as no-flow cells (Conan et al., 2003). Recharge was distributed according to SWAT simulation outputs for each day. River—aquifer interaction was simulated using a RIVER package for MODFLOW. The river stage of MODFLOW is imported from the daily simulation outputs of SWAT.

Results and discussion

Model calibration and validation

Calibration involves determining the magnitude and spatial distribution of the model parameters. These model parameters reproduce the observed system-states (hydraulic heads, stream flows) with time. The daily streamflow for three years running (2000—2002) was calibrated against the measured daily streamflow. Inputs to the model are physically based (i.e. based on readily observed or measured information). However, there is often considerable uncertainty in model inputs, due to spatial variability and measurement error etc. (Arnold and Allen, 1999).

Several variables were selected for calibration. These were: (1) ESCO — a soil evaporation compensation coeffi-

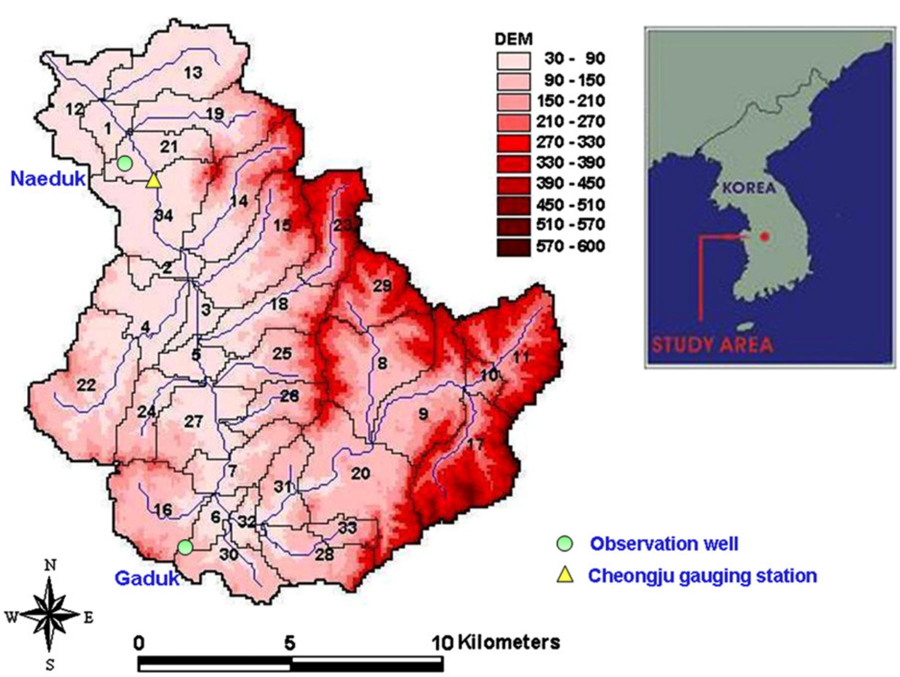

Figure 8 The Musimcheon Basin in South Korea with the up- and downstream gauging station locations.

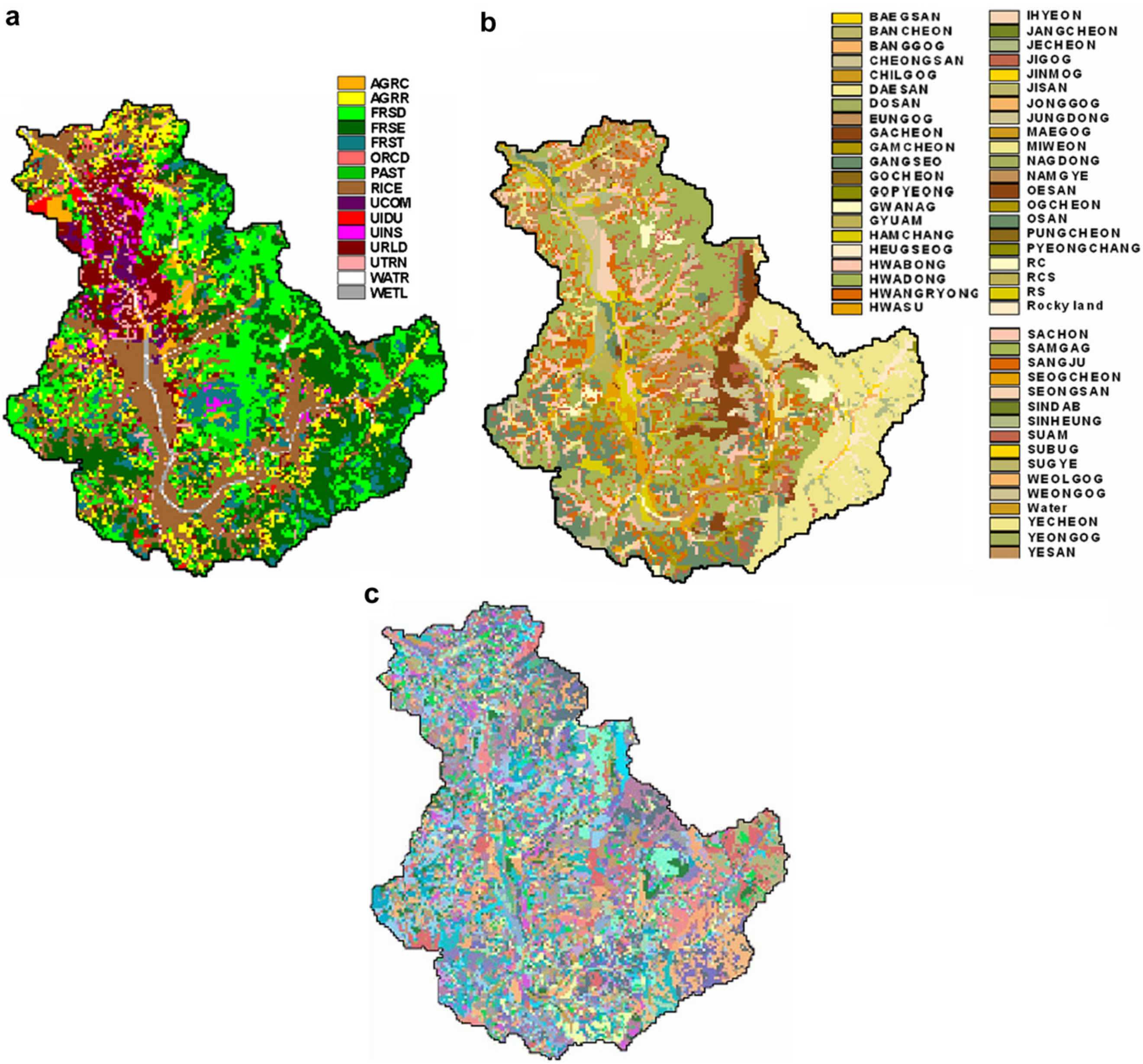

Figure 9 Land use map, soil type map and HRU distribution map in Musim Basin. (a) Land use map, (b) soil type map and (c) HRU distribution map.

cient; (2) AWC — plant available soil water capacity and; (3) CN2 — condition II runoff curve number. ESCO was allowed to vary between 0.95 and 1.0, indicating there was no compensation with depth. AWC is adjusted within a range given by the soil database (NIAST, 2005), which is ±0.05. CN2 is allowed to vary ±6% in order to account for uncertainty in the hydrologic condition of the basin according to a previous study (Arnold and Allen, 1999).

For the groundwater model, the primary calibration parameters were the aquifer hydraulic conductivity and storativity. The overall calibration procedure involved adjusting the SWAT parameters by trial and error. This ensured that the resulting recharge and runoff produced relatively low errors in streamflows. The hydraulic conductivity, the storativity and riverbed conductance were then optimized by a trial and error procedure. Minimizing the low flow error during dry season optimized these variables. Calibration was performed on the total stream flow. If the simulated and measured flows were within 10%, then calibration was terminated. The coefficient of determination (R^2) for daily flow at the Cheongju gauging station was 0.70 for the calibration period from 2001 to 2002.

In order to evaluate the performance of the integrated model, daily streamflows were simulated using the SWAT—MODFLOW model at the Cheongju gauging station during 2003—2005. The total flow for the entire basin yielded an R^2 of 0.71 for the validation period. This success might be a consequence of the flexibility of the MODFLOW model, which has a mechanism that more realistically accounts for groundwater flow.

Table 1 Land use classes in Musimcheon Basin

Item	Description	Area (km^2)	Percentage (%)
AGRC	Agricultural land — close-grown	4.74	2.39
AGRR	Agricultural land — row crops	18.42	9.29
FRSD	Forest — deciduous	38.80	19.58
FRSE	Forest — evergreen	46.63	23.85
FRST	Forest — mixed	12.68	6.40
ORCD	Orchard	0.71	0.36
PAST	Pasture	3.95	1.99
RICE	Rice	38.18	19.26
UCOM	Commercial	3.52	1.78
UIDU	Industrial	1.40	0.70
UINS	Institutional	3.34	1.68
URLD	Residential — low density	17.77	8.96
UTRN	Transportation	4.46	2.25
WATR	Water	1.79	0.90
WETL	Wetlands — mixed	1.84	0.93

Table 2 Soil type classes in Musimcheon Basin

Class	Area (km^2)	Percentage (%)	Class	Area (km^2)	Percentage (%)
CHEONGSAN	3.85	1.94	JISAN	2.14	1.08
PUNGCHEON	0.34	0.17	CHILGOG	0.03	0.02
HWANGRYONG	0.55	0.28	NAMGYE	2.79	1.41
YEONGOG	1.98	1.00	MIWEON	0.61	0.31
JIGOG	0.04	0.02	SANGJU	15.86	8.00
PYEONGCHANG	0.14	0.07	MAEGOG	0.06	0.03
ANRYONG	0.62	0.31	DOSAN	1.03	0.52
SEOGCHEON	5.16	2.60	WATER	1.27	0.64
SEONGSAN	0.69	0.35	HWADONG	1.13	0.57
JANGCHEON	0.12	0.06	JECHEON	1.93	0.97
SUGYE	0.01	0.01	SUAM	6.76	3.41
YONGJI	0.69	0.35	OESAN	6.52	3.29
HEUGSEOG	2.35	1.19	BAEGSAN	0.21	0.11
SINDAB	0.26	0.13	GANGSEO	2.48	1.25
OSAN	14.83	7.48	GACHEON	0.29	0.15
YESAN	8.28	4.18	SACHON	11.76	5.93
RCS	0.41	0.21	RC	1.01	0.51
DAESAN	26.13	13.18	OGCHEON	0.45	0.23
YECHEON	4.55	2.30	NAGDONG	1.07	0.54
GWANAG	2.43	1.23	HWASU	0.27	0.14
ROCKY LAND	0.58	0.29	GYUAM	1.77	0.89
GOPYEONG	0.13	0.07	GOCHEON	0.10	0.05
BANCHEON	0.02	0.01	RS	2.17	1.10
HAMCHANG	3.43	1.73	JINMOG	0.53	0.27
SAMGAG	43.24	21.81	WEOLGOG	1.02	0.51
JUNGDONG	2.58	1.30	GAMCHEON	5.98	3.02
BANGGOG	0.14	0.07	SUBUG	0.03	0.02
EUNGOG	3.55	0.28	IHYEON	1.45	0.73
HWABONG	1.35	0.68	JONGGOG	0.32	0.16
SINHEUNG	1.63	0.82	WEONGOG	0.09	0.05

The comparison of measured and simulated results for the entire period is shown in Fig. 10. The hydrograph was plotted using a log scale in order to emphasize the quality of low flow simulation. Fig. 10 shows a good agreement between measured and simulated hydrographs.

For comparison, the simulated hydrograph by SWAT was represented with the hydrograph of SWAT—MODFLOW, as shown in Fig. 11. The SWAT was not able to correctly reproduce the streamflow dynamics in low flow even after a comprehensive calibration. The differences in the low flows

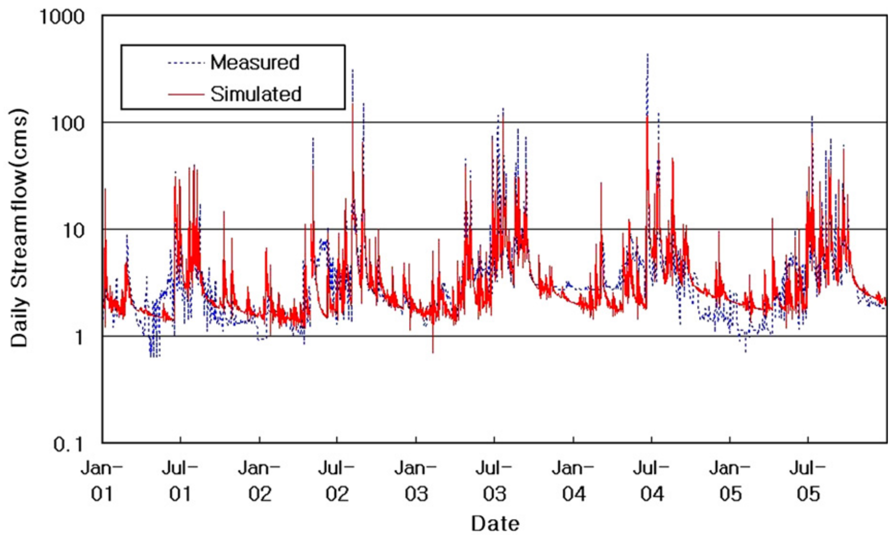

Figure 10 Simulation results by SWAT—MODFLOW at Cheongju gauging station.

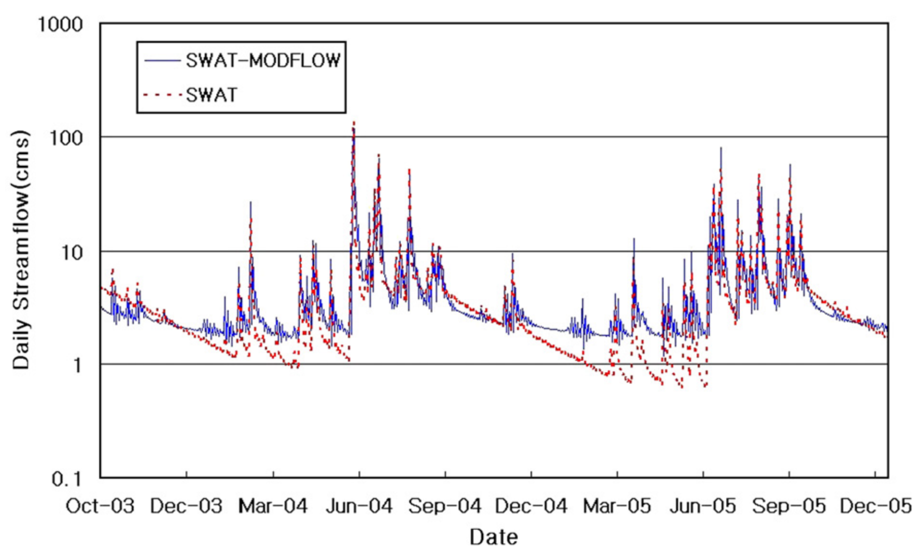

Figure 11 Comparison of the hydrographs reproduced by SWAT and SWAT—MODFLOW.

were due to insufficient baseflow resulting from the limitation of the groundwater module in SWAT. However, as previously shown in Fig. 9, an improved correspondence of measured and simulated daily streamflow in the low flow season was achieved by the SWAT—MODFLOW. Specifically, gradual or rapid variations of groundwater flow can be determined mainly by the river—aquifer exchange flow rate in SWAT—MODFLOW. This would be dependent on the head difference between the aquifer and the stream and on the aquifer properties such as hydraulic conductivity, storability, initial groundwater head and aquifer depth, etc.

SWAT is not able to represent the spatial distribution of the groundwater table because the model is an HRU-based quasi-distributed model rather than a grid-based fully-distributed model. Since SWAT—MODFLOW uses MODFLOW as the groundwater model, it is capable of calculating the spatially distributed groundwater table. Fig. 12 shows the measured and simulated groundwater table maps recorded on the 3rd of January 2004. Both figures show that the water table roughly follows the topographic slope. Visual inspection of the simulated groundwater table map shows the spatial variation with reasonable accuracy ($R^2 = 0.95$).

Fig. 13 graphically illustrates the simulated and observed groundwater level time-series at the Naeduk gauging station. The simulated time-series pattern follows the trend of the observed time-series, which reflects seasonal variations of groundwater levels. The results show that the differences between the simulated and the measured groundwater levels were acceptable.

Simulated groundwater recharge

SWAT—MODFLOW is also capable of simulating the spatio-temporal variation of groundwater recharge rates. Fig. 14 shows the simulated groundwater recharge map for the Musimcheon Basin recorded in July and August 2003. The

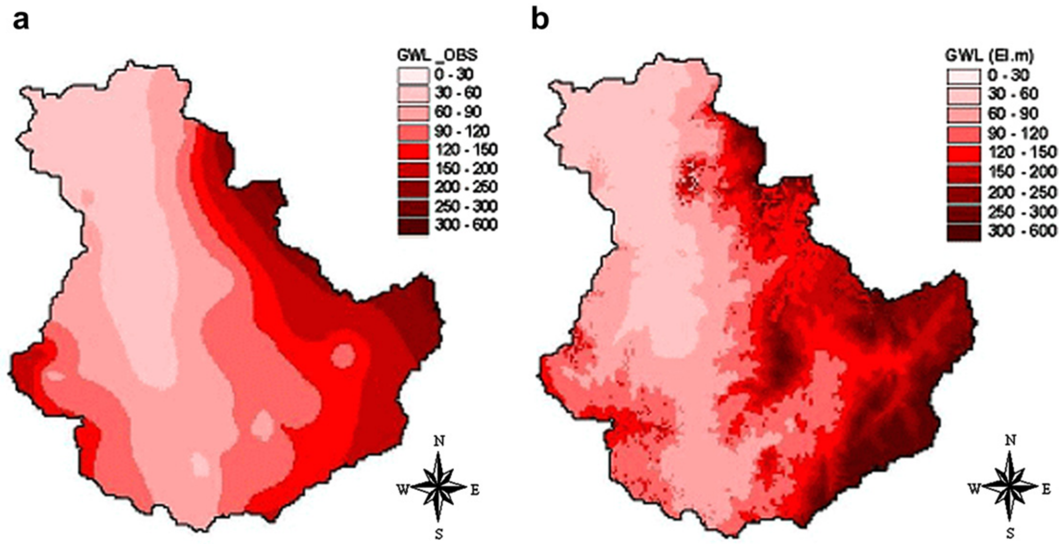

Figure 12 Spatial distribution of groundwater table simulated by SWAT-MODFLOW. (a) Measured groundwater table map and (b) simulated groundwater table map.

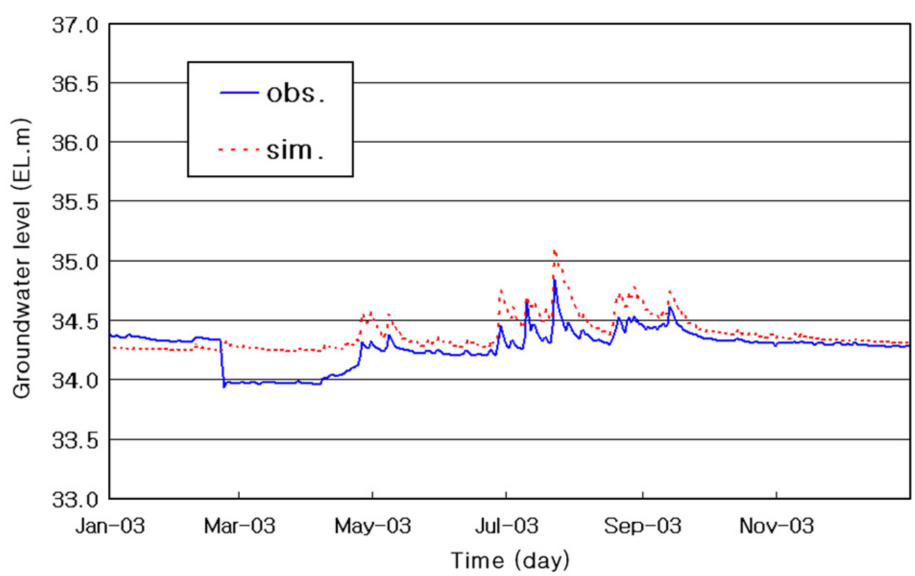

Figure 13 The simulated and observed groundwater level at the Naeduk gauging station.

calculated groundwater recharge ranges from less than 15 mm/month to more than 200 mm/month, reflecting the diversity of climatic conditions, soil types and depths, vegetation types and coverage, as well as slope variations.

At the East of the basin, the groundwater recharge, in general, was less than 30 mm/month. In this area, the major runoff fraction is discharged by direct runoff including lateral subsurface flow, due to the steep topographic slope. Along the stream network, the groundwater recharges were generally small, because of the soil type in this area.

Application of SWAT—MODFLOW pumping module

The advanced pumping module, which is added to the SWAT—MODFLOW model, was initially tested at the Musimcheon Basin in Korea. We consider the enhanced water transfer method when the source type is a shallow aquifer and the destination is outside of the watershed. In the integrated SWAT—MODFLOW model, pumping from the shallow aquifer is carried through the Well package of MODFLOW. In order to investigate the effects of pumping wells, the distribution of multiple wells are considered. Fig. 15a shows the spatially distributed 2176 pumping wells in the basin by using the report from MOCT (2006). The maximum pumping rate is considered to estimate the potential amount of groundwater development. Local water table depletion is observed in the highly pumped area where natural flow paths are modified by groundwater abstraction (Fig. 15b).

Due to this groundwater abstraction, the streamflow is as varied as the withdrawal of water during the stress period,

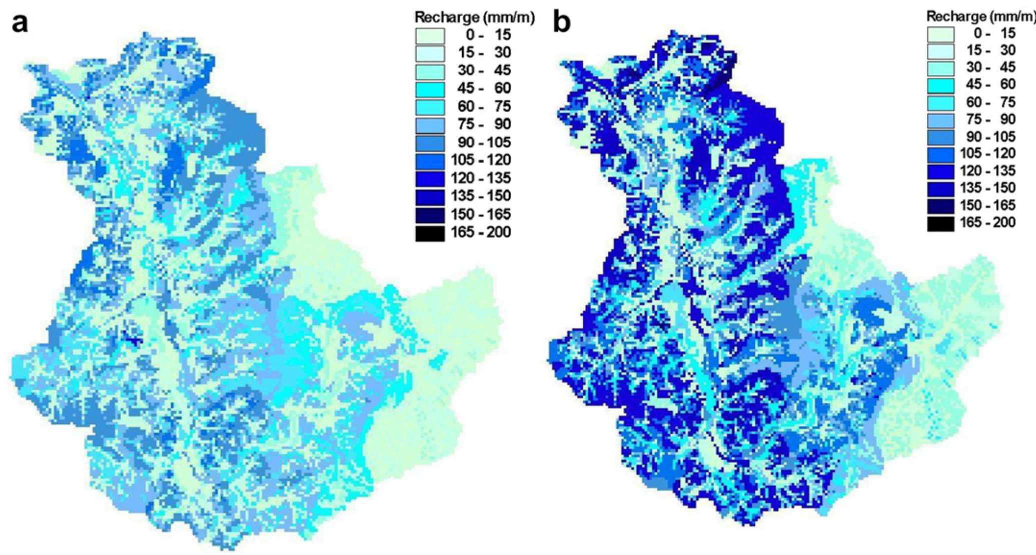

Figure 14 Estimated monthly recharge for studied basin in July and August 2003. (a) July and (b) August.

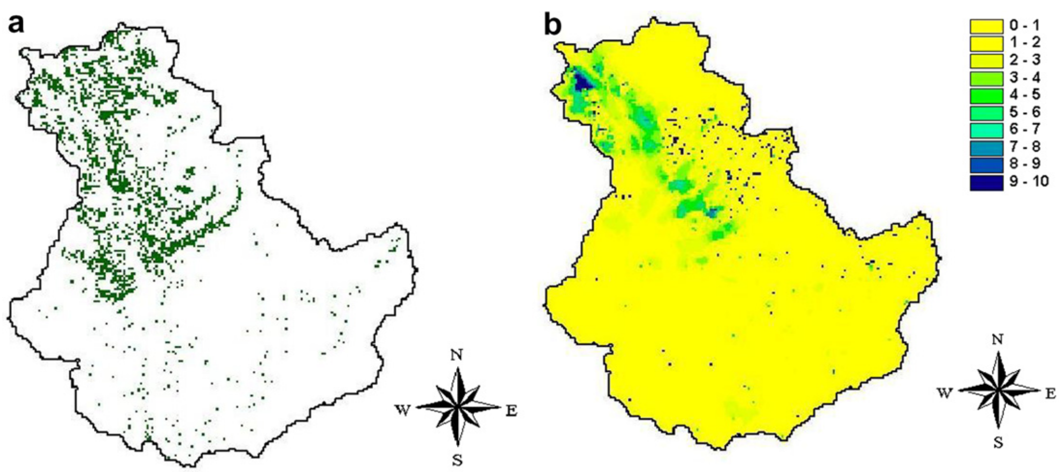

Figure 15 Estimated groundwater drawdown at 1000 days after pumping simulation. (a) Distribution of wells and (b) distribution of drawdown.

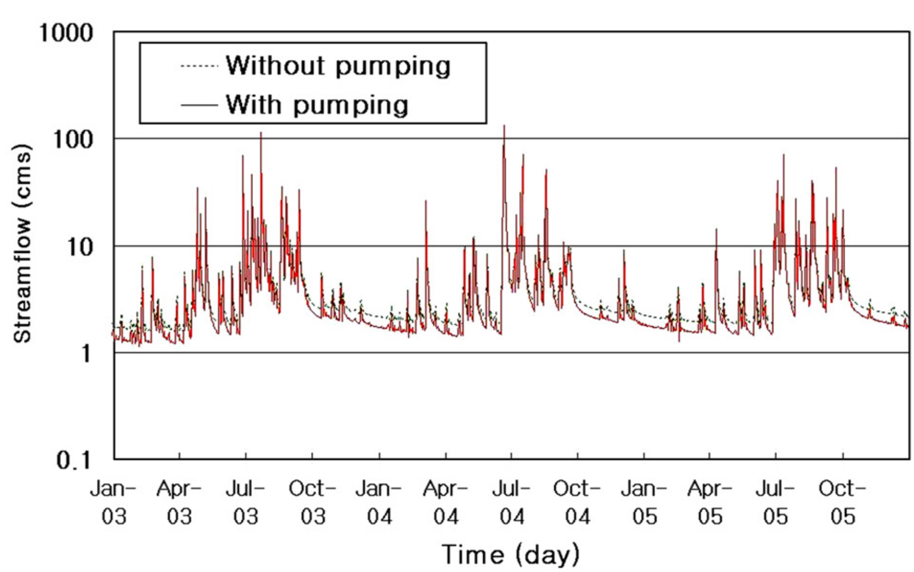

Figure 16 Streamflow variation due to well pumping in the watershed.

as shown in Fig. 16. Fig. 16 demonstrates that the integrated model suggested in this work is able to represent the surface water hydrologic components as well as the groundwater components, including the groundwater recharge and the artificial withdrawal of water. Without an adequate estimate for recharge, the impacts of withdrawing groundwater from an aquifer cannot be properly assessed, and the long-term behavior of an aquifer under various management schemes cannot be reliably estimated (Sophocleous, 2005). Therefore, this model could be very effective, when considering the discharge to a stream, spring or marsh, for the planning of the development of sustainable amounts of groundwater.

Conclusion

In this study, the newly integrated SWAT–MODFLOW model is described and demonstrated. We developed an HRU–cell conversion interface which exchanges flow data between the cells in MODFLOW and the HRUs (hydrologic response units) of SWAT. HRUs are defined by overlaying soil and landuse and lumping similar soil/land use combinations. On the basis of these modifications, the groundwater model in SWAT was successfully replaced with MODFLOW. Therefore, it was possible to establish a fully integrated modeling program, which was able to form a linkage in each time step. Therefore, the distributed groundwater recharge rate and the groundwater evapotranspiration can be effectively simulated. Considering the interaction between the stream network and the aquifer to reflect boundary flow completes the linkage. For this purpose, the RIVER package in MODFLOW is used for river–aquifer interaction. The water transfer method in SWAT is enhanced in order to use daily/monthly/yearly water transfer options as well as either a constant amount, a constant rate, or a minimum value from the water source. The application demonstrates that an integrated SWAT–MODFLOW is capable of simulating the spatio-temporal distribution of groundwater recharge rates, aquifer evapotranspiration and groundwater levels and that it enables an interaction between the saturated aquifer and channel reaches. This interaction played an important role in the generation of groundwater discharge in the Musimcheon Basin, especially during the low flow period. The distributed drawdown and a reduced stream flow by pumping were successfully reproduced by using the advanced water transfer method in SWAT, linked with the Well package in MODFLOW. The comprehensive results demonstrate that the model is able to represent the integrated watershed modeling results that contain surface hydrologic components and groundwater hydrologic components such as distributed recharge rates, groundwater levels and discharge, with or without well pumping.

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